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Hybrid Solar Still with Thermoelectric Generators and Evacuated Tubes

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ABSTRACT

Evacuated tube solar collectors (ETSC) are commonly used for heating water purposes in residential, commercial and industrial applications. ETSC provides better heat collection efficiency since it reduces conduction and convection heat transfer losses to the environment. A thermo electric generator (TEG) is a solid-state generation technology that converts heat directly into electricity without employing any moving parts. It is based on the Seebeck effect, that is, the temperature difference maintained across the opposite faces of the thermo electric cell develops a proportional potential difference across the thermo-junctions, therefore creating electricity. In the present paper, the concept of using TEGs for cleans power electric generation, when coupled with ETSC. The proposed Hybrid Solar Still system consists of eight ETSC, 8 thermoelectric modules. To maintain a reasonable temperature difference across the TEGs and maximize the efficiency, the heat transfer fluid will be in upper level in solar still and TEM's are mounted just above the ETSC on the solar still. The design of the proposed system is to provide electric power as well as hot water. The proposed combined TEG and ETSC system has the potential to provide electric power for residential and remote area applications, with zero emissions.

Keywords - *Thermoelectric generator system, Hybrid Solar Still, Evacuated tubes.*

1. INTRODUCTION

Solar energy, like all other renewable energies, is very safe and environmentally friendly. The average solar power received on the Earth's surface is 1.2x1017 W. This means that the energy supply from the Sun hitting the Earth in an hour can meet the total energy consumption on Earth for a whole year. Scientists estimate that sunlight can provide 10,000 times the amount of energy needed to fulfill humanity's current energy needs. Electricity generation and the escalating costs of fossil fuels over the last few years, have forced governments and engineering bodies to re-examine the whole approach to building design and control. Global energy consumption is set to increase to 60% by the year 2020. [1]

India is situated in the sun belt between the latitudes of 40 degree south and 40 degree north with a suitable seasonal variation (from 4 to greater than 7.5 kW / m2 / day) and annually averaging nearly 5.5 kW / m2 / day over nearly 60% of the landscape. India has the second highest population in the world with an escalating energy demand. Unfortunately over 400 million people do not have access to electricity and nearly 84740 [2] un-electrified villages in the country, calling for alternate power sources for various needs.

This analysis of the global population growth and energy consumption is also associated with increasing load on non-renewable energy resources, the conventional fossil fuels such as coal, oil and gas, which are likely to deplete with time and the use of which is also hazardous to environment. Renewable energy is energy obtained from sources that are essentially inexhaustible such as solar power which can be harnessed without the release of harmful pollutants. [3]

A major portion of the world's electricity production is still fossil-fuel based, but higher fossil-fuel prices together with increasing concerns over energy security and climate change will boost the share of renewable-based electricity in the future years (world energy outlook fact sheet 2009). Heat energy also forms a large fraction of the total energy consumption as the industrial process heat (IPH) as well as for household such as bathing, washing, food processing etc. The processes such as boiling distillation and polymerization that require heat input are common in chemical industries. This heat is often supplied as hot water in the range from 20 to 260^{0}C. [4]

1.1 Evacuated-Tube Solar Collector

The evacuated-tube solar collector has become the most popular design for solar water heating in the past decades. Evacuated tubes absorb of the solar rays. They absorb solar energy converting it into heat for use in water heating. Evacuated tubes have already been used for years in Germany, Canada, China and the UK. There are several types of evacuated tubes in use in the solar industry. The most common collectors use "twin-glass tube". This type of tube is chosen for its reliability, performance and low manufacturing cost. Each evacuated tube consists of two glass tubes made from extremely strong borosilicate glass. The outer tube is transparent allowing light rays to pass through with minimal reflection. The inner tube is coated with a special selective coating (Al-N/Al), which features excellent solar radiation absorption and minimal reflection properties. The top of the two tubes is fused together and the air contained in the space between the two layers of glass is pumped out while exposing the tube to high temperatures. This "evacuation" of the gasses forms a vacuum, which is an important factor in the performance of the evacuated tubes.

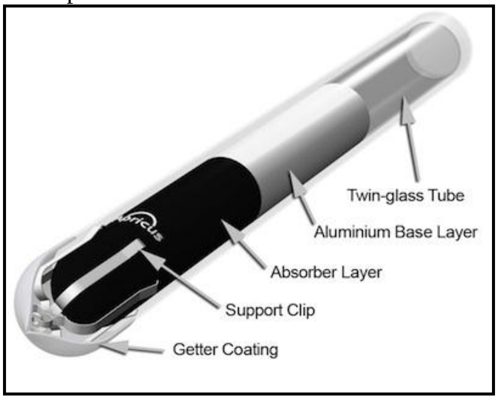

Fig 1.1: Evacuated tube

The name "evacuated" is used to describe the process that expels the air from within the space between the tubes, forming a vacuum. A vacuum is an excellent insulator against heat loss, and so evacuated tubes are able to operate very efficiently when there is a big difference between the inside of the tube and the outside ambient air. For this reason evacuated tubes are the ideal choice for high temperature hot water applications or locations that get cold in the winter. In order to help maintain the vacuum over the 15-20 year life of the evacuated tube, a barium getter "soaks up" any remaining gases in the evacuated chamber plus any fresh gases such as Nitrogen that can slowly permeate through the glass over time, a process known as out-gassing. This barium layer also provides a clear visual indication of the vacuum status; the silver-colored barium layer turns white if the vacuum is lost making it easy to identify a fault tube.

The combination of the highly efficient absorber coating and the vacuum insulation means that the coating can be well over 200^{o}C / 392^{o}F and the outer glass is cool to touch.

Fig 1.2: Evacuated tube solar collectors.

The evacuated-tube solar collectors currently take more than 80% of solar water heating market. The glass evacuated-tube solar collectors have better thermal efficiencies at the higher temperature than the conventional flat-plate solar collectors and they are suitable for applications at the temperature of above 80^{0}C.

When the average water temperature increases from 50^0C to 90^0C, the thermal efficiency of the evacuated-tube solar collector decreases from about 60% to 50%. On the other hand, the water temperature is usually required in the range of 35^0 to 50^0C for domestic hot water or space heating. These imply that with a small expense of its thermal efficiency, an evacuated tube solar collector may be used at a higher temperature to drive a combined water heating and power generation. One attractive option is to incorporate the evacuated tube solar collectors with thermoelectric modules to produce additional electricity besides its hot water production. Compared with solar heat driven mechanical power generation, thermoelectric modules are much more suitable for small-scale applications as they are reliable, light and compact, and have no mechanical moving parts. They are also friendly to the environment as no working fluid is used. The conversion efficiency of the thermoelectric module influences the overall cost and efficiency significantly. In this project work an attempt is made to develop economical model for improving the efficiency and reducing the costs of STEGS, by combining evacuated glass tube with standard thermoelectric modules, as this enables a greater portion of the collected solar energy to be converted into useful forms.

1.2 Thermoelectric Generator

Thermoelectric phenomenon was discovered nearly two hundred years ago. Since last sixty years the practical applications from thermoelectric had been exploited. The first breakthrough that would eventually be used to form the thermoelectric effect was discovered in 1820. Several other breakthroughs in the field were discovered over the next few decades but their relationship was not realized for a full 38 years. William Thomson discovered that heat is absorbed or produced when current flows in material with a certain temperature gradient and that the heat is proportional to both the electric current and the temperature gradient. His publication linked all the discoveries from the preceding decades.

Thermoelectric Generator which is also known as Peltier module is widely used in the market for several cooling applications. Use of TE modules often gives an answer to many critical thermal management problems, where low to moderate amount of heat is concerned.

A thermoelectric device is in essence a simple heat engine which converts licit energy directly into electricity or the reverse. Its operation is based on the three well known interrelated phenomena of Seebeck, Peltier and Thomson effects.

In its simplest form a thermoelectric generator is formed of it and n-type pellet connected electrically in series and thermally in parallel, as shown in figure no.1.6. The hot junction temperature is maintained by a heat flux from a heat source while the cold junction temperature is maintained by a heat sink. The generator operates as an electron-gas Rankine cycle, where the energy level of the electrons is raised at the hot junction and lowered at the cold junction. Due to the temperature difference, charge carriers with energy level clear tile energy level at the hot end will be easily excited to a high energy level and can lower their energies by diffusing to the cold end. Similarly those at the cold end can diffuse toward the hot end at a rate dependent on their energies. Thus, a net current of charge carriers will result .This flow will cause the charge carriers to pile up at one end of the element, usually the cold end, and thereby produces an electromotive force (emf). [5]

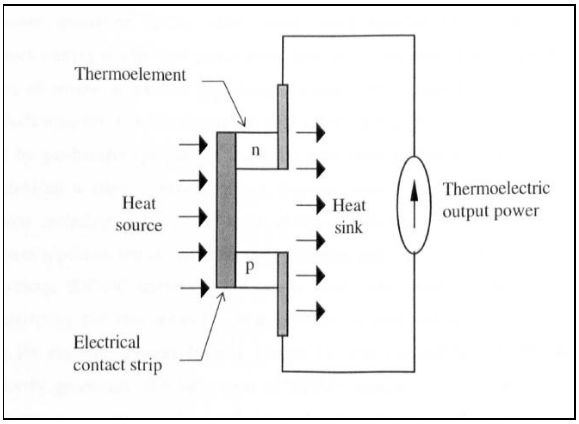

Fig 1.3: Working of thermoelectric devices.

1.3 Single Basin Solar Still with Evacuated Tubes

The solar radiation is transmitted through the glass cover and captured by a black surface at the bottom of the still. A shallow layer of water absorbs the heat which then produces vapour within the chamber of the still. The sunlight entering the still is absorbed by the water and the container. The result is that the molecules and ions absorb the energy. Some of the water molecules absorb enough energy to break free from the liquid water and become gaseous molecules flying about inside the container. The vapour condenses on the glass cover, which is at a lower temperature because it is in contact with the ambient air, The water molecules lose more energy as they join together forming droplets of pure water which run down into the cup.

It is important for greater efficiency that the water condenses on the plate as a film rather than as droplets, which tend to drop back into the saline water. For this reason the plate is set at an angle of 10^0 to 20^0.

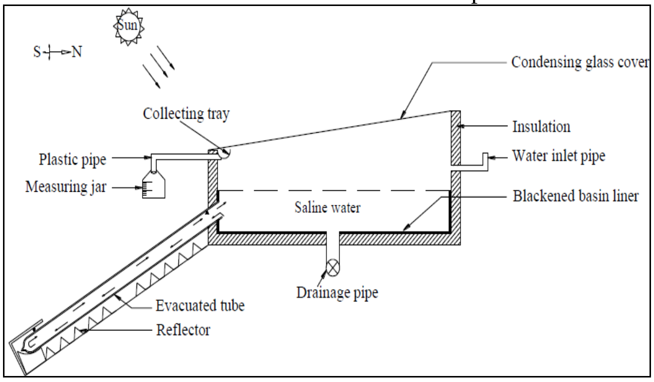

Fig 1.4: Schematic diagram of Single Basin Solar Still with evacuated tubes.

2. METHODOLOGY

2.1 Selection of Thermoelectric Generators

The TEG modules are selected considering few factors such as dimensions, optimum temperature range, availability of the product etc. The TEG module used in the current work was supplied by Mars-eshop. The model no. of the module is TEC1-12706. The module material is Bismuth Telluride of dimension 40×40×3.80mm. Each module contains 127 junctions that are formulated for optimum Seebeck effect. The thermal elements in the module are thermally and electrically in series combination for maximum Seebeck coefficient. Perimeter is sealed for moisture protection. TEG module can be operated in the temperature range -60^0 C to $+140^0$C.

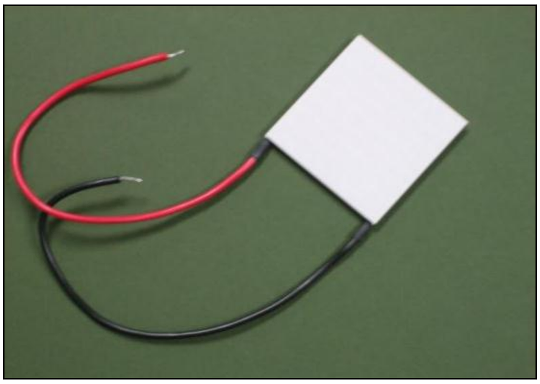

Fig 2.1: Thermoelectric Module TEC1-12706.

Product Specification:

- Operational Voltage: 12VDC
- Current max: 6amps
- Voltage max: 15.2VDC
- Power max: 92.4 Watts

A. Experimental Set up

The Experimental setup can be divided in different parts as follows,

1. Fabrication of Solar Still
2. Evacuated tubes Solar Collectors
3. Assembly of Thermoelectric Generator
4. Cooling arrangement

The experimentation was done on the experimental set up fabricated after going the literature survey. The schematic diagram of the experimental set up is as follows.

Fig 2.2: Actual experimental set-up

2.2 Fabrication of Solar still

Solar still is built by using a mild steel sheet metal with a thickness of 0.2mm and was designed considering the assembly constraints (one face is made 300 inclined to get assembled with tube and structure support) and volume requirement. Sheet metal operations like blanking, punching and bending were done and finally fabricated using Gas welding.

Specifications of the Solar Still:

Material	Mild Steel
Length	710mm
Width	230mm
Height	230mm
Gap Between adjacent Tubes	5mm
volume	40ltr

Table 2.1: Specifications of Solar Still

2.3 Evacuated Tube Solar Collector

Eight numbers of Evacuated tube solar collectors were used to conduct this experiment and specification of the same is mentioned below:

Length	1570mm
Diameter	47mm

Table 2.2: Specification of ETSC

2.4 Assembly of Thermoelectric Modules

The arrangement of thermoelectric generator modules should be such that the thermoelectric generator module should get completely sandwiched between hot side and cold side. In this project the thermoelectric generator modules are sandwiched between the hot side storage tank and cold side is left open for without cold water running, and closed for cold water running. For assembly, the thermal grease is applied on the hot side thermoelectric module. The thermoelectric generator modules hot side is facing the inclined surface of the storage tank i.e. just above the evacuated tube solar collector holes with its cold side facing the surrounding. For cooling system that is for cold water running, cold side of module is made to come in contact with cold water running system.

2.5 Cooling Arrangement

The cold sides of the module are made to come in contact with cold water running system. The modules are sandwiched between hot side of the inclined face of Solar Still and cold side of cold water running system. The cold water running system contains bottle with ice water i.e. cold water and a passage to run the cold water and made to come in contact with thermoelectric module cold side.

2.6 Measurements

For experimentation, instruments were used. The varying elements are temperatures at different points, output voltage and current. The instruments used are listed as follows.

2.7 Portable Thermometer

The measuring temperature range is in between 0-500K. It is used to measure temperature at hot side tank water temperature (T_h) and cold side temperature (T_c).

2.8 Multimeter

The output obtained here is Direct current type therefore digital Multimeter is used to measure voltage and current respectively.

3. EXPERIMENTAL PROCEDURE

This project work is aimed at capture the solar energy and converts the maximum possible received energy into the electrical energy and thermal energy. The evacuated tube solar collectors in 8 nos. are used to receive the solar radiation. The evacuated tube solar collectors get heated due to solar energy. Thus temperature difference is created across the thermoelectric modules resulting into the electrical output. Eight nos. of thermoelectric modules connected in series are used in this project. The heat from storage tank water is passed to the modules. The water in the tank keeps modules hot which gets heated over time and can be used as hot water for household or industrial purposes. The electrical power produced can be stored in battery for use at night.

For experimentation the project setup is placed at prominent place so as to receive direct solar. The modules terminal is connected to the Multimeter for Current and Voltage readings. The water about forty liters is filled in the tank. The reading of temperature at hot side, cold side and tank water are noted hourly along with voltage and ampere from 09:00hrs to 16:00hrs. Following are the readings noted hourly during experimentation.

T_C - Temperatures at Cold side of TEM respectively.

T_H - Temperature of water in storage tank.

ΔT - Temperature difference across the modules.

V, I, P-- Voltage, current and power output from TEMs respectively.

4. OBSERVATIONS AND CALCULATIONS

Tc - Temperatures at cold ends of TEM.

T_H - Temperature of water in storage tank.

ΔT - Temperature difference across the modules.

T_M - mean temperature of the hot and cold sides of the TEGs

V, I, P - Voltage, current and power output from TEMs respectively

Sample Calculations

1. Power output = Voltage * current [6]

2. Total Heat Energy Gained by Water in 9 Hrs = mass of water* Sp. heat of water*change in temp of water = $m*Cp*\Delta T_h$

3. Temperature difference (ΔT) = $T_h - T_c$

4. Seebeck coefficient = Voltage/Temperature difference = $V/\Delta T$ [8]

5. Figure of Merit (Z) Z = $\alpha^2/(R*K)$ [1]

Thermal to electrical conversion efficiency of TEM

$$\eta_c = \frac{Th-Tc}{Th}\left[\frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+(\frac{Tc}{Th})}\right] \quad (7)$$

$T_M = (T_h + T_c)/2$

6. Gross Surface Area Of Evacuated Tube Solar Collector = π*Diameter * Length * no. of tubes

7. Avg. Solar Energy Received by Evacuated Tubes = Avg. solar insolation* gross surface area of evacuated tube = I_b*A_s

Efficiency of Solar Thermoelectric Generator (STEG) = (Avg. Electrical O/P + Avg. Thermal O/P)/ Avg Solar Energy Received.

4.1 Day without Cooling Water

Sl	Tm	Sb=V/ΔT	Z	ZTm	Efficiency (%)
	K	V/K	K^{-1}		
1	294	0	0	0	0
2	298.1	0.0258	8.456x10-5	0.0252	0.012
3	301.95	0.0233	6.896x10-5	0.0208	0.017
4	305.9	0.02463	7.688x10-5	0.0235	0.026
5	309.6	0.0279	9.889x10-5	0.0306	0.041
6	311.15	0.02841	1.02x10-4	0.0317	0.045
7	312.2	0.03043	1.174x10-4	0.0366	0.052
8	314.5	0.03421	1.485x10-4	0.0467	0.068
9	313.5	0.02777	9.747x10-5	0.0305	0.043

Table 4.1: Calculation Table - Thermal to electrical conversion efficiency of TEM.

4.2 Day with Cooling Water

Sl	Tm	Sb=V/ΔT	Z	ZTm	Efficiency (%)
	K	V/K	K^{-1}		
1	288.5	0.0741	6.975x10-4	0.2012	0.45
2	291.1	0.0993	1.252x10-3	0.3644	0.85
3	293.75	0.1098	1.531x10-3	0.4497	1.17
4	295.75	0.1417	2.550x10-3	0.7541	1.85
5	296.5	0.1912	4.644x10-3	1.3769	2.9
6	297.1	0.2502	7.952x10-3	2.3625	4.09
7	297.55	0.2949	0.011048	3.2851	5.21
8	297.5	0.2933	0.010928	3.2513	5.11

Table 4.2: Calculation Table - Thermal to electrical conversion efficiency of TEM.

5. RESULT

5.1 Variation of Voltage with Temperature Difference

Without cold water *With cold water*

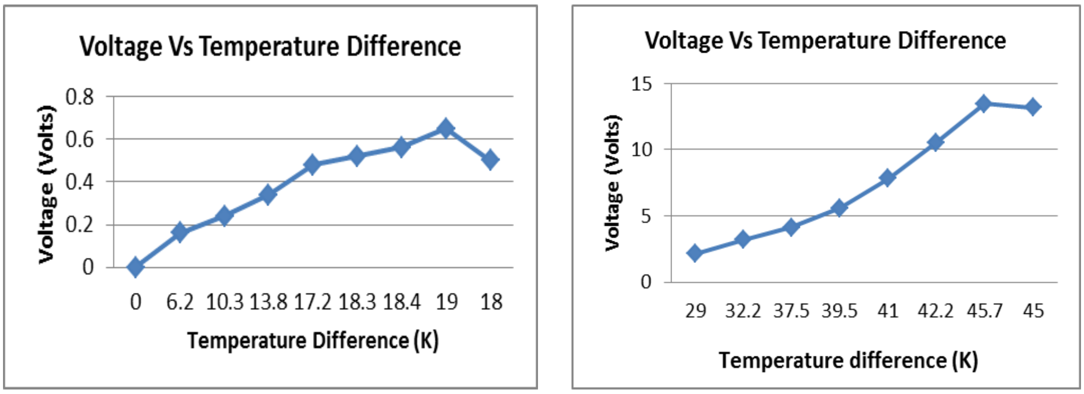

Fig 5.1: Variation of voltage with temperature difference

The graph shows that voltage varies directly with temperature difference. The output voltage increases at beginning, to the maximum value at maximum temperature difference. Then voltage drops as the temperature difference reduces. The rate of voltage rise is high at beginning due to rapid increase in solar insolation and value of Seebeck coefficient. [6]

5.2 Variation of Power with Temperature Difference

Without cold water *With cold water*

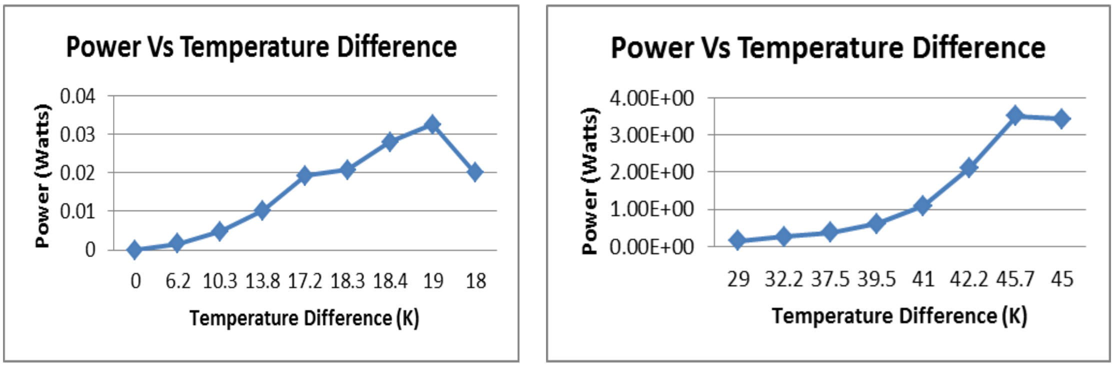

Fig 5.2: Power output as a function of temperature difference.

As shown in graphs, the power output increases with temperature difference. The increase in voltage results in the increase in power output from thermoelectric module. [7] The output power increases at beginning, to the maximum value at maximum temperature difference. Then power output drops as the temperature difference reduces. The rate of rise is high at beginning due to rapid increase in solar insolation. The drop in power output is gradual with drop in temperature difference.

5.3 Variation of Figure of Merit with Mean Temperature

Without Cold Water *With cold water*

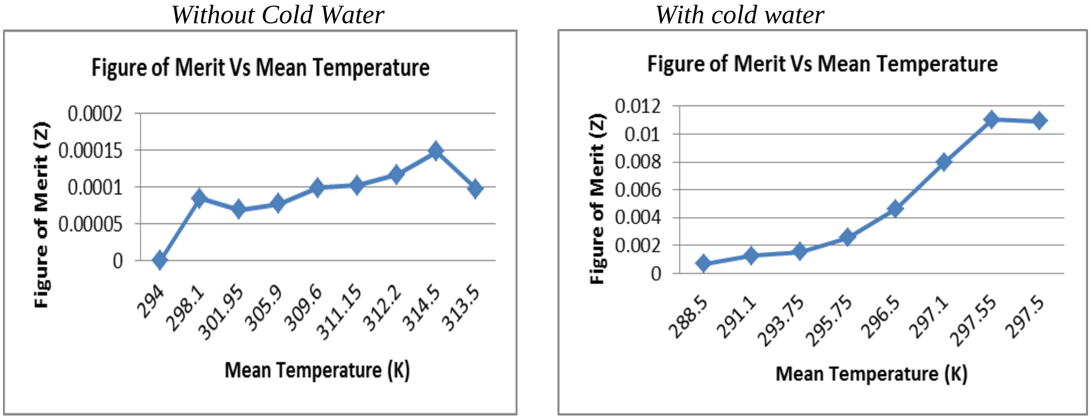

Fig 5.3: Variation of the figure of merit with mean temperature.

The non-dimensional number Figure of merit shows the ability of the thermoelectric generator to produce voltage when subjected to temperature difference. Figure of merit is a function Seebeck coefficient α, resistance R and thermal conductance of thermoelectric material k.

As shown in the graphs, the figure of merit drops sharply to minimum value with the rise in mean temperature. This initial sharp drop in Z is due to small increase in voltage as compared to large rise in temperature difference. It then rises gradually with rise in mean temperature, as rise in temperature difference is gradual in this range and voltage is rising steadily.

5.4 Variation of Conversion Efficiency with Hot Side Temperature

Without Cold water *With cold water*

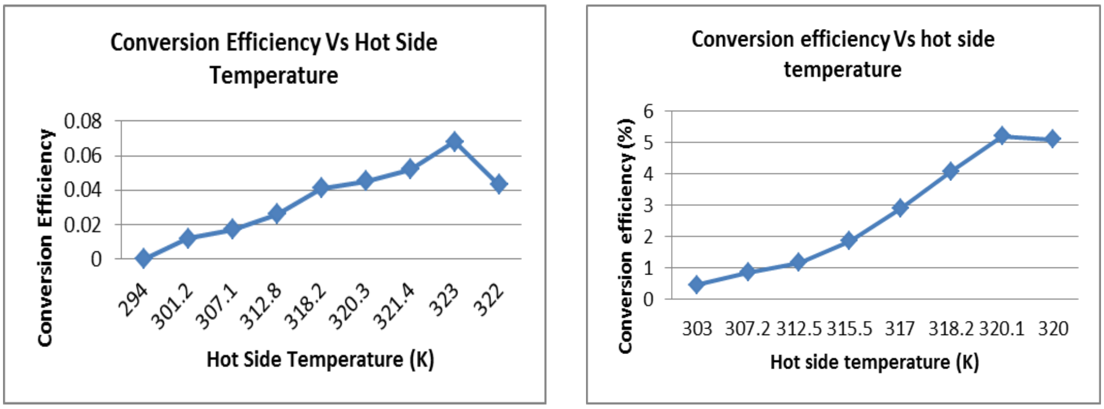

Fig 5.4: Conversion efficiency Vs hot side temperature

The graphical representation of Conversion efficiency with hot side temperature is shown in graphs. The graphs shows that conversion efficiency increases gradually as hot side temperature increases up to maximum value, and then it decreases. The conversion efficiency is the function of figure of merit, and hot and cold side temperatures. Figure of merit decreases after certain mean temperature, therefore conversion efficiency also follows the path of figure of merit.

5.5 Variation of Power with Time

The electrical power generated by the solar thermoelectric generator system as a function of time over a 8-day period. The graphs show that with increase in solar insolation, the temperature difference across the thermoelectric modules can also be seen to increase. A larger temperature difference across the thermoelectric modules, which is proportional to the heat transfer rate, improves the thermal electromotive force generated by the Seebeck effect and increases the output electrical power. The output electric power of the solar thermoelectric generator system increased sharply with increasing solar insolation between the hours of 11:00hrs to 14:00hrs, reaching a peak around noon. It then drops gradually to 16:00 hrs. [7]

Without Cold water *With cold water*

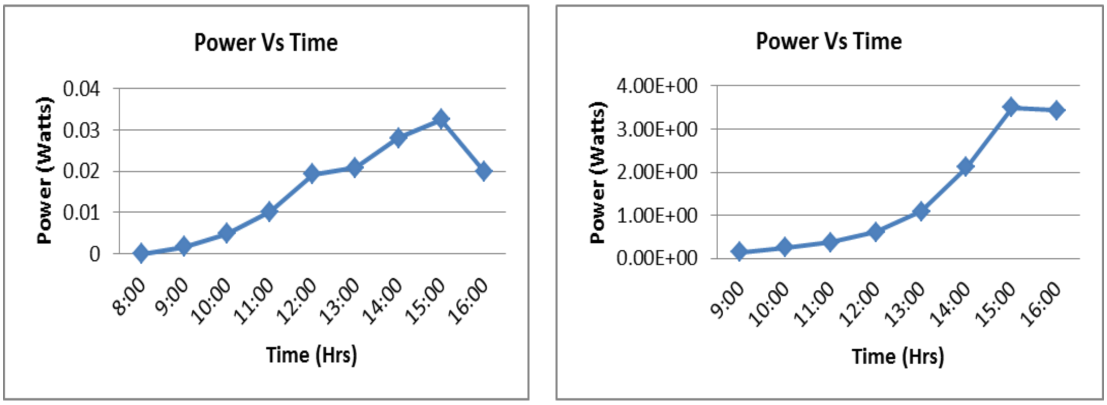

Fig 5.5: Output power as a function of time.

6. CONCLUSIONS

- In this project work, Hybrid Solar Still with Thermoelectric Generator and Evacuated Tubes, this can supply both electricity and heat simultaneously.
- It has been shown from the experimental result that the system is capable of producing electrical power and heating the water in a day. The TEG power increases with temperature difference.

- This prototype is having capacity to mount more thermoelectric generating modules which can increase power, figure of merit of the generator and hence the conversion efficiency for the same generator and corresponding to same temperature difference.
- Power produced by the thermoelectric generator increases with increase in hot side temperature which can be done by increasing number of evacuated tube solar collectors.
- Higher temperature resistance thermoelectric module along with better generator design can improve power output.
- Hybrid Solar Still made from evacuated tubular solar collectors with integrated TEGs are easy to fabricate and only slightly more expensive than solar collectors on their own.
- The Hybrid Solar Still with Thermoelectric Generator and Evacuated Tubes can supply electric energy and hot water simultaneously, will have a wide field of application and require little maintenance, making them ideal for providing power to regions where there is as yet no electricity network.

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